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Developing methodologies for large scale wave and tidal stream marine renewable energy extraction and its environmental impact: an overview of the *TeraWatt* project

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- Licensing arrangements for marine renewable energy (MRE) developments must consider potential environmental effects.
- These include the single, combined and cumulative effects of multi-site MRE developments over a wider region.
- We introduce here a "toolbox" of datasets and methods to quantify the effects of wave and tidal stream MRE developments.
- These were applied to the area of greatest MRE development potential in Scottish waters (Pentland Firth and Orkney Waters).

This article presents an introduction and overview of a modelling project "TeraWatt: Large scale interactive coupled 3D modelling for wave and tidal energy resource and environmental impact".

The project was funded by the SUstainable PowER GENeration (SUPERGEN) "Marine Hub". SUPERGEN (http://www.rcuk.ac.uk/research/xrcprogrammes/energy/energyresearch/supergen) is an initiative of the Research Councils UK (RCUK) Energy Programme, led by the Engineering and Physical Sciences Research Council (EPSRC). It is focused on supporting resilient and sustainable generation, supply, transmission and storage of the UK's energy. The Marine Challenge addresses the UK Centre for Marine Energy Research's (UKCMER) mission to support the wave and tidal energy sector beyond their current state of development.

TeraWatt ran from June 2012 until the end of November 2015 and was conducted by a consortium constituted under the Marine Alliance for Science and Technology for Scotland (MASTS) pooling initiative. The consortium was led by Heriot-Watt University and included the University of Edinburgh, University of Strathclyde, University of Swansea, University of the Highlands and Islands (Lewis Castle College and Scottish Association for Marine Science) and Marine Scotland Science (MSS). Marine renewable energy (MRE) developers were also fully engaged and supported many aspects of the work (see Fig. 1).

Scotland has substantial wave and tidal MRE resources and is at the forefront of the development of marine renewable technologies and ocean energy exploitation. Within Scottish waters, a significant proportion of the wave and tidal energy resource is located in the Orkney Islands and the stretch of water that separates them from the Scottish mainland, the Pentland Firth (collectively referred to the Pentland Firth and Orkney Waters area, PFOW). MRE developments in Scottish waters are subject to licensing conditions under the responsibility of Scottish Ministers. As part of the licensing arrangements, environmental effects in the immediate vicinity of devices and arrays will be addressed in the EIA (Environmental Impact Assessment) process that each developer must undertake. It is essential, however, that the regulatory authorities understand how a number of multi-site developments collectively impact on the physical and biological processes over a wider region, both in relation to cumulative effects of the developments and marine planning responsibilities. At a regional scale, careful selection of sites may enable the optimum exploitation of the resource while minimising any environmental impacts to an acceptable level. MSS is the Science Division of the Marine Scotland Directorate of the Scottish Government, responsible for providing scientific advice to the licensing authority.

The objectives of TeraWatt are fourfold: Firstly, to minimise delays in array licensing by providing answers to 3 specific questions identified by MSS as critical for the regulatory authorities, responsible for the licensing of wave and tidal developments; and, secondly, to collect the methodologies used to answer these into a "methods toolbox" that can be more widely utilised for EIA, and in which the MRE developer community has confidence. Much of the toolbox description has been reported in a collection of "Position Papers" that are listed below in association with their respective workstreams. The peer review papers included in this special issue contribute to the description of such methodology and are also listed below. For other project dissemination outputs, see Table 1.

The three "research questions" and a fourth "research activity", the compilation of methodologies, linked directly to the workstream structure of the project, are detailed below (Workstreams 2-4). In addition, Workstream 1 defined these research questions and addressed a number of logistical activities (data acquisition and management, characterization of realistic array scenarios, identification of acceptable impacts criteria and dissemination/knowledge exchange activities). Data acquisition is described in O'Hara Murray (2015a) and O'Hara Murray and Gallego (this issue). Realistic array characterisation is described in O'Hara Murray (2015b). The regulatory framework and acceptable impact criteria are discussed by Gallego et al. (this issue).

Research Question 1: What is the best way to assess the wave and tidal resource and the effects of energy extraction on it? The objectives here were to: i) produce methodologies that will increase our knowledge and confidence in coupled hydrodynamic models of wave and tidal systems using case studies validated by field data; ii) produce methodologies for the incorporation of multisite wave and tidal arrays within i) to illustrate changes in the resource in the near and far field from energy extraction; iii) produce methodologies for the determination of resource potential under different scenarios of exploitation; and iv) determine extreme wave and tidal conditions for the parameterisation of modelling of physical and environmental consequences. These were mapped as deliverables from Workstream 2 ("Wave and tidal stream modelling"). See Waldman *et al*. (this issue), Venugopal *et al*. (this issue), MacIver et al. (2015) and Baston *et al*. (2015).

Research Question 2: What are the physical consequences of wave and tidal energy extraction? The objectives here, making use of outputs from Workstream 2, were to: i) produce methodologies for linking those outputs to coupled models of sediment transport, again with illustrations validated by available field data; ii) investigate changes in sediment transport patterns occurring as a consequence of energy extraction and examine effects on seabed morphology; iii) determine the effect of energy extraction on suspended sediments; and iv) determine effects on the shoreline and coastline using also the extreme wave distributions from Workstream 2. These were mapped as deliverables in Workstream 3 ("Sediment dynamics"). Output from this workstream is presented by Fairley *et al.* (this issue), Heath et al. (this issue), Fairley and Karunarathna (2015), Sabatino *et al.* (2015) and Heath *et al*. (2015).

Research Question 3: What are the ecological consequences of wave and tidal energy extraction? The objectives were to: i) produce methodologies for statistical models that will enable benthic biotope characterisation, using given physical parameters and outputs from Workstreams 2 and 3, illustrating these and validating them with field data; ii) demonstrate what changes in these may occur as a consequence of various energy extraction scenarios; and iii) evaluate other potential ecological effects. These were mapped as deliverables from Workstream 4 ("Ecological Consequences of wave and tidal energy extraction"). Some delays in the completion of these activities prevent us from introducing here the output of this workstream.

Research Activity 4: The overarching objective of the research was to generate a suite of methodologies (a "toolbox") to provide a better understanding of, and be used to assess, changes to the resource from energy extraction, and the potential physical and ecological consequence. The consequent methodology was demonstrated on a key MRE development area, the PFOW, and its availability as a toolbox should enable the acceleration of wave and tidal stream MRE array deployments there. The output of this workstream is: i) a combination of the articles presented in this special issue; ii) the Position Papers listed above; iii) the datasets compiled by the project, which are available to the wider community (O'Hara Murray and Gallego (this issue), O'Hara Murray (2015a)), with the exception of a small number of restricted datasets purchased for use within the project; and iv) code used to perform tasks such as large scale processing of inputs for the model runs, available via open source repositories. The arrangements for the management and organisation or the research are shown in Fig. 1.

As a result of TeraWatt, we have developed a comprehensive repository of the best available data for use in MRE modelling studies for the Pentland Firth and Orkney Waters and wider Scottish Shelf and have fulfilled our goal of developing realistic array scenarios in the context of regulatory approaches to the first developments in this area. As advised by MRE industry during the development of the original proposal, our use of industry standard modelling software means the methodologies and much of these data can be readily employed in common by industry, academia and regulators (see Gallego *et al*., this issue). The engagement of industry in several project activities (e.g. workshops, Steering Group – see Table 2) also means that there is a shared understanding of the toolbox of developed methods. During this research we also made recommendations to commercial software developers for improvements to their code. However, the main focus of our research has been providing key shared knowledge of this promising sector to the scientific community, regulatory authorities, developers and interested stakeholders. The collection of journal papers introduced by this article covers all aspects of our work and draws out the key messages of our project.

Acknowledgements

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References

Baston, S., Waldman, S. and Side, J. (2015) Modelling energy extraction in tidal flows. In TeraWatt Position Papers – A "toolbox" of methods to better understand and assess the effects of tidal and wave energy arrays on the marine environment. MASTS, St. Andrews. pp. 75-108. ISBN 978-0-9934256-0-8.

Fairley, I., Karunarathna, H. and Chatzirodou, A. (this issue) Modelling the effects of marine energy extraction on non-cohesive sediment transport and morphological change in the Pentland Firth and Orkney Waters.

Fairley, I. and Karunarathna, H. (2015) Modelling the impacts of marine energy extraction on non-cohesive sediment transport and morphodynamics. In TeraWatt Position Papers – A "toolbox" of methods to better understand and assess the effects of tidal and wave energy arrays on the marine environment. MASTS, St. Andrews. pp. 109-128. ISBN 978-0-9934256-0-8.

Gallego, A. et al. (this issue) Large scale three-dimensional modelling for wave and tidal energy resource and environmental impact: methodologies for quantifying acceptable thresholds for sustainable exploitation.

Heath, M.R., Sabatino, A.D., Serpetti, N.and O'Hara Murray, R.B. (2015) Scoping the impact tidal and wave energy extraction on suspended sediment concentrations and underwater light climate. In TeraWatt Position Papers – A "toolbox" of methods to better understand and assess the effects of tidal and wave energy arrays on the marine environment. MASTS, St. Andrews. pp. 143-166. ISBN 978-0-9934256-0-8.

Heath, M., Sabatino, A., Serpetti, N., McCaig, C. and O'Hara Murray, R. (this issue) Modelling the sensitivity of suspended sediment profiles to tidal current and wave conditions.

MacIver, R., Reddy, N.T. and Venugopal, V. (2015) Representing Wave Energy Extraction in Regional Scale Numerical Models. In TeraWatt Position Papers – A "toolbox" of methods to better understand and assess the effects of tidal and wave energy arrays on the marine environment. MASTS, St. Andrews. pp. 49-74. ISBN 978-0-9934256-0-8.

O'Hara Murray, R.B. (2015a) Data acquisition and processing for TeraWatt. In TeraWatt Position Papers – A "toolbox" of methods to better understand and assess the effects of tidal and wave energy arrays on the marine environment. MASTS, St. Andrews. pp. 9-30. ISBN 978-0-9934256-0-8.

O'Hara Murray, R.B. (2015b) Tidal stream and wave energy array scenarios for the Pentland Firth and Orkney Waters Strategic Area. In TeraWatt Position Papers – A "toolbox" of methods to better understand and assess the effects of tidal and wave energy arrays on the marine environment. MASTS, St. Andrews. pp. 31-48. ISBN 978-0-9934256-0-8.

O'Hara Murray, R. and Gallego, A. (this issue) Data acquisition and the development of realistic tidal and wave energy scenarios for numerical modelling of Orkney Islands waters, Scotland.

Sabatino, A.D., Clement, R., Heath, M.R. and McKee, D. (2015) Use of ocean colour remote sensing to monitor sea surface suspended sediments. In TeraWatt Position Papers – A "toolbox" of methods to better understand and assess the effects of tidal and wave energy arrays on the marine environment. MASTS, St. Andrews. pp. 129-142. ISBN 978-0-9934256-0-8.

Venugopal, V., Nemalidinne, R. and Vögler, A. (this issue) Numerical modelling of wave energy resources and assessment of wave energy extraction by large scale wave farms.

Waldman, S., Baston, S., Nemalidinne, R., Chatzirodou, A., Venugopal, V. and Side, J. (this issue) Implementation of tidal turbines in MIKE 3 and Delft3D models of Pentland Firth & Orkney Waters.

Figure Legends

Figure 1: Key activities and relationships in TeraWatt research

Authors	Year	Title	Journal/Conference	DOI (if available)	Workstream
Adams, T.P., Miller, R.G, Aleynik, D & Burrows, M.T.	2014	Offshore marine renewable energy devices as stepping stones across biogeographical boundaries	Journal of Applied Ecology	10.1111/1365-2664.12207	WS4
Baston, S., Harris, R.E., Woolf, D.K., Hiley, R., Side, J.	2013	Sensitivity analysis of the turbulence closure models in the assessment of tidal energy resource in Orkney	Proceedings of the 10th EWTEC Conference, Aalborg, Denmark	10.13140/2.1.3033.3762	WS2
Chatzirodou, A., Karunarathna, H.	2014	Numerical modelling of sea bed morphodynamics associated with tidal energy extraction	3rd Oxford Tidal Energy Workshop (OTE2014)		WS3
Chatzirodou, A., Karunarathna, H.	2014	Impacts of tidal energy extraction on sea bed morphology	34th International Conference in Coastal Engineering, Seoul, Korea	10.9753/icce.v34.sediment.33	WS3
Chatzirodou, A., Karunarathna, H., Reeve, D.E.	2015	Modelling the response of sandbank dynamics to tidal energy extraction	Proceedings of the 36th IAHR World Congress, The Hague, Netherlands		WS3
Chatzirodou, A., Karunarathna, H. and Reeve, D.E	2015	Modelling the morphodynamic response of subtidal sandbanks to tidal energy extraction	3rd IMA International Conference on Flood Risk in Swansea University		WS3
Chatzirodou, A. and Karunarathna, H.	2015	Impacts of tidal energy extraction on sea bed morphology	10th UK Young Coastal Scientists and Engineers Conference, Cardiff University		WS3
Chatzirodou, A. and Karunarathna, H.	2015	Modelling the response of subtidal sandbanks to tidal energy extraction	36th IAHR World Congress, The Hague, The Netherlands		WS3
Chatzirodou, A., Karunarathna, H. and Reeve, D.E.	In press	Investigation of deep sea shelf sandbank dynamics driven by highly energetic tidal flows	Marine Geology		WS3
Coll, J., Woolf, D.K., Gibb, S.W,. Challenor, P.	2013	Sensitivity of ferry services to the Western Isles of Scotland to changes in wave and wind climate	Journal of Applied Meteorology and Climatology	10.1175/JAMC-D-12-0138.1	WS2
Fairley, I., Karunarathna, H.	2014	The morphodynamics of a beach in the lee of wave energy converter	2nd International Conference on Environmental Interactions of Marine		WS3

		arrays	Renewable Energy Technologies (EIMR2014)Technologies (EIMR2014)		
Fairley, I., Karunarathna, H.	2016	Assessing the importance of including waves in simulations of tidal stream turbine impacts	RENEW2016, Lisbon, Portugal		WS3
Fairley, I., Masters, I., Karunarathna, H.	2015	Numerical modelling of storm and surge events on offshore sandbanks	Marine Geology	10.1016/j.margeo.2015.11.007	WS3
Fairley, I., Karunarathna, H. and Masters	2015	Sediment transport in the Pentland Firth and impacts of tidal stream energy extraction	EWTECC2015, Nantes, France		WS3
Fairley, I., Masters, I., Karunarathna, H.	2015	The cumulative impact of tidal stream turbine arrays on sediment transport in the Pentland Firth	Renewable Energy	10.1016/j.renene.2015.03.004	WS3
Fairley, I., Masters I. and Karunarathna, H.	2016	Numerical modelling of storm and surge events on offshore sandbanks	Marine Geology		WS3
Goddijn-Murphy, L., Woolf, D.K., Easton, M.	2013	Current Patterns in the Inner Sound (Pentland Firth) from Underway ADCP Data	Journal of Atmospheric and Oceanic Technology	10.1175/JTECH-D-11-00223.1	WS1
Greenwood, C. & Christie, D.	2014	A frequency independent method for the simulation of Disturbances around a small scale wave farm using a Boussinesq simulation.	2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies (EIMR2014)	10.13140/2.1.2783.8720	WS2
Greenwood, C. & Christie, D.	2015	The simulation of oscillating wave surge converters using a Boussinesq model: Wave disturbances around an array.	Proceedings of the 25th Annual International Ocean and Polar Engineering Conference, Hawaii		WS2
MacIver, R. & Glleizon, P.	2015	Wave-current interaction in the Pentland Firth and Orkney Waters	Proceedings of the 11th European Wave & Tidal Energy Conference (EWTEC), Nantes, France		WS2
Masters, I., Williams, A.J., Croft, N., Togneri, M., Edmunds, M., Zangiabadi, E., Fairley,	2015	A comparison of numerical modelling techniques for tidal stream turbine analysis	Energies	10.3390/en8087833	WS2

I., Karunarathna, H.					
Sabatino, A.D., McCaig, C., O'Hara Murray, R.B., Heath, M.R.	2015	Modelling wave-current interactions off the east coast of Scotland	Ocean Science Discussions	10.5194/osd-12-3099-2015	WS2
Venugopal, V., Nemalidinne, R.	2015	Wave resource assessment for Scottish waters using a large scale North Atlantic spectral wave model	Journal of Renewable Energy	10.1016/j.renene.2014.11.056	WS2
Venugopal, V., Nemalidinne, R. & Vögler, A.	2015	Impact of Temporal Variation of Wind Input on Wave Parameters Prediction Using Numerical Wave Model	Proceedings of the 11th European Wave & Tidal Energy Conference (EWTEC), Nantes, France		WS2
Waldman, S., Miller, C., Baston, S., Side, J.	2014	Comparison of two hydrodynamic models for investigating energy extraction from tidal flows	2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies (EIMR2014)	10.13140/RG.2.1.2523.0960	WS2
Waldman, S., Genet, G., Baston, S., Side, J.	2015	Correcting for mesh size dependency in a regional model's representation of tidal turbines	Proceedings of the 11th European Wave & Tidal Energy Conference (EWTEC), Nantes, France	10.13140/RG.2.1.3571.6726	WS2
Woolf, D. K.	2013	The strength and phase of the tidal stream	International Journal of Marine Energy	10.1016/j.ijome.2013.11.001	WS2
Zangiabadi, E., Edmunds, M., Fairley, I., Togneri, M., Williams, A.J., Masters, I., Croft, N.	2015	Computational fluid dynamics and visualisation of coastal flow in tidal channels supporting ocean energy development	Energies	10.3390/en8065997	WS2

Table 1: Listing of TeraWatt project dissemination outputs (excluding articles in this issue and Position Papers), as recorded in the RCUK's Gateway To Research website (http://gtr.rcuk.ac.uk) at the time of writing. Any outputs not currently in the public domain are available from the authors on request.

The Marine Alliance for Science and Technology Scotland (MASTS) **Overall Management** of the Project – Chair of Steering Group and lead on **Knowledge Exchange** activities	Knowledge Exchange

STEERING GROUP

EPSRC UKCMER, Marine Scotland, Marine Management Organisation, Crown Estate, Wave and Tidal Device and Field Developers and Financier

Project Management Committee

MASTS plus PI and all Cis from the Workstreams

Workstream 1 (lead Marine Scotland Science)	Workstream 2 (lead University of Edinburgh)	Workstream 3 (lead Strathclyde and Swansea Universities)	Workstream 4 (lead Heriot-Watt University)
Regulatory Requirements Research Questions Data collection, collation and compilation. Realistic Array Configurations for subsequent workstreams Acceptance Criteria Stakeholder Dialogue	**Wave and Tide Modelling** Parameterisation of energy extraction Coupled wave tide models and validation with field data Models of energy harvest based on realistic array configurations Determination of extreme states Parameterisation for Workstream 4 Review of methodologies for Methods Toolbox	**Sedimentary Modelling** Models of sediment transport and suspended sediment distributions and validation Changes in these, and in shoreline and coastal processes with energy harvesting Parameterisation for Workstream 4 Review of methodologies for Methods Toolbox	**Ecological Modelling** Statistical models for benthic biotope characterisation and distribution, and their validation. Model re-runs with energy harvesting to evaluate change Evaluation of these and related workstream outputs for marine ecosystems. Review of methodologies for Methods Toolbox

Methods Toolbox

Methods for the parameterisation of energy extraction within industry modelling approaches, differentiation of coupled wave/tide models, determination of extreme states, methods for the evaluation of change in sediment transport, suspended sediment and benthic biotope distributions and for the evaluation of related ecosystem effects. Published Position Papers to summarise these outputs.

Knowledge Exchange:

Project Launch Knowledge Exchange Workshop at All Energy

Regular quarterly reporting to EPSRC UKCMER

Reporting to MASTS Annual Science Meetings

Developer Workshops

Contributions to the work of ICES Working Groups and Annual Science Conference

Other international conferences

Final Developer Workshop/end of Project Event